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ORIGINAL ARTICLE

Risk management strategies to cope with climate change in grassland production: an illustrative case study for the Swiss plateau

Robert Finger · Pierluigi Calanca

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Abstract In this paper, we assess climate change impacts on an intensively managed grassland system at the Swiss Plateau using the process-based grassland model PROGRASS. Taking the CO_2 fertilization into account, we find increasing yield levels (in the range of 10–24%) and sharp increases in production risks for an illustrative climate change scenario that suggests a marked increase in temperature and decrease in summer rainfall. Climate change–induced increases in the coefficients of variation of grassland yields are in the range of 21 and 50%. This finding underpins that additional risk management strategies are needed to cope with climate-change impacts on grassland production. The outputs from the grassland model are evaluated economically using certainty equivalents, i.e., accounting for mean quasi rents and production risks. To identify potential risk management strategies under current and future climatic conditions, we consider adjustments of production intensity and farm-level yield insurance. The impact of climate change on production intensities is found to be ambiguous: farmers' will increase intensity under unconstrained production conditions, but will decrease production intensity in the presence of a cross-compliance scheme. Our results also show that the considered insurance scheme is a powerful tool to manage climate risks in grassland production under current and future conditions because it can reduce the coefficients of variation of quasi rents by up to 50%. However, we find that direct payments tend to reduce farmers' incentives to use such insurance scheme.

R. Finger (✉)
ETH Zurich, Zurich, Switzerland
e-mail: rofinger@ethz.ch

P. Calanca
Agroscope Reckenholz-Tänikon Research Station ART,
Zurich, Switzerland

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Introduction

Climate change is expected to affect agricultural production through changes in the temperature and precipitation regime and elevated atmospheric CO_2 concentrations (see e.g., Olesen and Bindi 2002; Fuhrer 2003; Easterling et al. 2007; Torriani et al. 2007; Schaap et al. 2011). The direction and magnitude of the impacts will depend on the specific cropping system as well as on regional conditions (Bindi and Olesen 2010), but there is little doubt that adaptation measures at several levels are required (Risbey et al. 1999; Kandlikar and Risbey 2000). Concerning the agronomic practice, these adaptation options would primarily relate to changes in land use (e.g., changes in crop and cultivar choice) and crop management (e.g., changes in input use, irrigation and sowing dates) (see e.g., Olesen and Bindi 2004; Orlandini et al. 2008). From an economic perspective, the expansion of existing as well as the introduction of new agricultural insurance products may assist farmers in coping with climate change–induced changes in their income risks (e.g., Smit and Skinner 2002; Torriani et al. 2008).

Climate-change impacts and adaptation in grasslands are of particular importance because grasslands are a major contributor to global food production, covering about 70% of the world's agricultural area (Soussana and Lüscher 2007). Previous studies have shown that climate change could not only affect grassland productivity, but also impact fodder quality and amplify weed problems (Calanca and Fuhrer 2005; Fuhrer et al. 2006; Soussana and Lüscher 2007). Moreover, climate change is expected to increase production risks by increasing yield variability (Finger et al. 2010). Due to the latter finding, agricultural insurances are expected to offer a valuable contribution to adaptation. In addition, adjustments in production intensities, in particular due to fertilizer use, can help to mitigate negative impacts of climate change and reduce production risks (e.g., Finger et al. 2010, 2011).

In this paper, we analyze the potential of these adaptation strategies, i.e., insurance use and adjustments of production intensities, in the context of climate-change impacts on grassland systems of the Swiss Plateau. To this end, we use the process-based grassland model PROGRASS (Lazzarotto et al. 2009, 2010) which is combined with an economic valuation approach that accounts for mean profitability and production risks of grassland production. Our analysis also accounts for the role of direct payments and cross-compliance requirements for production decisions. The choice of this case study was motivated by the fact that Swiss grasslands, by providing the necessary input to animal production, represent the backbone of the agricultural sector (Calanca and Fuhrer 2005). At present, combined peril (or multi-risk) insurances that are available to Swiss farmers to cover risks in grassland production only contemplate risks associated with hail, storm, floods, excessive snow cover and landslides. However, no insurance scheme is available that covers also risks related to drought and excess precipitation. Based on this background, we examine in this paper the potential of farm-level yield insurance that provides coverage against *all* possible natural risks (Bielza et al. 2008). Similar insurance schemes for grassland and pasture production are already established in North America (e.g., Dismukes et al. 1995; Gloy and Staehr 2009).

Methodology

In a first step, we use the process-based grassland model PROGRASS to simulate intensive grassland production under current and future climatic conditions with different levels of nitrogen application. We consider an intensively managed grass/clover system on the Swiss Plateau (Oensingen, 7°44′E, 47°17′N, 450 m a.s.l., see also Ammann et al. 2007). The use of a biophysical model that accounts for above- and below-ground processes as well as for the interactions between plant functional types is necessary to sufficiently account for the complexity of typical Swiss grassland systems and to develop projections of grassland production.

In a subsequent step, the output of this grassland model is evaluated economically, accounting for mean quasi rents (revenue minus variable costs) but also for production risks. To this end, we employ certainty equivalents that account for the mean as well as the dispersion and the skewness of quasi rents. The economic analysis comprises the choice of the farmer to use specific amounts of fertilizer, to receive direct payments (with the associated cross-compliance requirements) and to adopt farm-yield insurance. This analysis allows us to evaluate farmers' adaptation options and to assess the effects of farm-level yield insurance schemes on farmers' income under current and future climatic conditions.

Data generation with PROGRASS

We consider a grassland system consisting of a mixture of two plant functional types, a tall-growing grass (*Lolium perenne* L.) and a short-growing white clover species (*Trifolium repens* L.). Such mixtures are typical for intensive grasslands on the Swiss Plateau. For this system, we estimate annual production under current and future climatic conditions and with respect to different levels of nitrogen applications using the PROductive GRASland Simulator (PROGRASS) (Lazzarotto et al. 2009, 2010). PROGRASS is a process-based model and accounts for key aspects of intensive grassland dynamics, in particular above- and belowground interactions between plant functional types relatively to light interception and the acquisition of soil mineral nitrogen (N) in response to climate and nitrogen application. The model is driven with hourly weather data, and requires specification of management options relatively to the cutting and fertilization regime (cutting dates, dates of the fertilizer applications), as well as specification of initial conditions for above- and belowground biomass, the soil organic and mineral N pools and the soil moisture storage. Further details concerning the model structure and requirements can be found in Lazzarotto et al. (2009, 2010). As it explicitly considers the effects of elevated CO_2 concentrations on plant dynamics (photosynthesis, stomatal conductance, biological N fixation) (Lazzarotto et al. 2010), atmospheric CO_2 abundances also need to be set.

As described in Lazzarotto et al. (2009), the model was parameterized using data from a long-term free-air CO_2 enrichment experiment run from 1993 to 2002 in Switzerland (Hebeisen et al. 1997) and was tested with respect to data collected since 2001 at our study site in Oensingen. As shown in Lazzarotto et al. (2009), the model can accurately reproduce dry-matter production, and relative plant-functional type's abundances in grassland systems as often encountered on the Swiss Plateau. Moreover, the model is able to realistically capture the effects of fertilization (Lazzarotto et al. 2009).

Following Finger et al. (2010), the effects of fertilization on grassland systems are examined by considering 10 different levels of mineral N application, with annual rates

Table 1 Climate-change scenario: Changes in monthly climate statistics between 2071–2100 and 1961–1990

	Δr [−]	$\Delta\tau$wet [−]	$\Delta\tau$dry [−]	ΔTmax [°C]	ΔTmin [°C]	$\Delta\sigma T$ [−]	ΔGR [−]
January	0.10	−0.09	−0.35	3.51	3.07	−0.20	0.07
February	0.44	0.19	−0.27	2.57	2.11	−0.21	−0.02
March	0.26	0.01	−0.30	1.93	1.38	−0.04	0.00
April	−0.01	−0.14	0.11	2.99	2.15	0.18	0.14
May	−0.23	−0.47	0.23	3.58	2.49	0.11	0.16
June	−0.28	−0.28	0.75	4.07	2.89	0.33	0.13
July	−0.47	−0.23	1.21	5.64	3.49	0.23	0.14
August	−0.31	−0.25	0.79	7.05	4.28	0.13	0.17
September	−0.28	−0.14	0.34	5.95	4.00	0.00	0.12
October	−0.02	−0.19	0.08	4.40	3.00	0.11	0.16
November	−0.34	−0.18	0.34	3.39	1.64	−0.04	0.32
December	0.06	0.15	−0.08	3.37	2.58	−0.21	0.23

Changes (Δ) in monthly climate statistics between 2071–2100 and 1961–1990 simulated by the regional climate model CHRM for the Swiss Plateau under the assumption of an A2 emission scenario. Changes in mean rainfall rate (r), duration of wet (τwet) and dry (τdry) spells, global radiation (GR) and inter-annual standard deviation of air temperature (σT) are relative; changes in daily maximum (Tmax) and minimum (Tmin) air temperature are absolute. *Source*: Finger et al. (2010)

varying from 50 to 500 kg ha^{-1} in steps of 50 kg ha^{-1}. Furthermore, five cuts per year are assumed, which represents intensive management of grassland in Switzerland.[1]

Two climate scenarios are considered. The first (BASE scenario) reflects current conditions (1981–2007), the second (Climate Change) represents climatic conditions as projected for 2071–2100 under the assumption of an A2 emission scenario (Nakicenovic et al. 2000) in a numerical experiment carried out with the CHRM regional model (Vidale et al. 2003) in the context of the EU PRUDENCE project (Christensen and Christensen 2007). This particular scenario was selected because it indicates very substantial shifts in the regional climate of the Swiss Plateau (Table 1), in particular concerning the summer precipitation regime, and a marked increase in atmospheric CO_2 burden (with a nominal value of 700 ppm as an average for 2071–2100).

Because the output of climate models is generally biased (Hansen et al. 2006; Schmidli et al. 2006), the hourly weather data necessary as input to PROGRASS were obtained for both scenarios using a two-step downscaling procedure.

In a first step, the LARS-WG stochastic weather generator (Semenov and Barrow 1997; Semenov et al. 1998) was applied to obtain daily weather data for minimum and maximum temperature, rain and solar radiation for both the BASE and climate-change scenarios. As in the study by Lazzarotto et al. (2010) the weather generator was conditioned using daily weather observations for 1981–2007 obtained from an operational weather station (Wynau, 7°47′E, 47°15′N, 422 m a.s.l.) located close to our study site. This calibration generated a series of monthly statistics (semi-empirical distributions of wet and dry spells length, rainfall amounts, minimum and maximum temperature, solar radiation; auto- and cross-correlations for minimum and maximum temperature and solar radiation) that were subsequently used to simulate synthetic data. For simulations under the constraints imposed by a climate scenario, the statistics listed in Table 1 were used to modify relevant parameters of the generation process (see e.g., Semenov 2007, for details). Although the values in Table 1 had to be derived assuming 1961–1990 as a reference (i.e., the reference period in the PRUDENCE experiments), the statistics of Table 1 were internally rescaled in LARS-WG to account for the fact that the observational data cover the period 1981–2007. Daily values of the minimum/maximum relative humidity (needed to estimate the water vapor pressure) were further calculated from solar radiation using statistical relations fitted to the observations for each month of the year and were assumed to be valid also under future climatic conditions (Lazzarotto et al. 2010).

In a second step, the synthetic daily data from LARS-WG were post-processed according to Thornley and France (2007) to calculate hourly data needed to drive PROGRASS. For radiation, a weighted average of a full sine and half sine curve were used to mimic the diurnal cycle, whereas for temperature and relative humidity, a sinusoidal progression was assumed, with maxima and minima at dawn and 3 h after solar noon, respectively. In addition, daily precipitation sums were uniformly distributed over 24 h, and wind speed was assumed constant at 1 m s^{-1}. As emphasized in Lazzarotto et al. (2010), the quality of the hourly data was tested indirectly by assessing the difference in key PROGRASS outputs as computed driving the model with observed or synthetic data. Relatively to grassland production at Oensingen, no significant difference was found.

To limit the amount of data (recall that the two climate scenarios are examined in combination with 10 N application scenarios), only 25 years of synthetic weather data were generated at hourly resolution for both the BASE and climate-change scenarios. Finally, note that the use of a stochastic weather generator with respect to the current climate was motivated by the necessity to ensure consistency between the two time frames.

[1] Because this study considers only intensive production, fertilizer use below $N = 50$ kg N ha^{-1} year^{-1} as well as lower numbers of cuts are not taken into account.

Calculation of quasi rents

In order to evaluate the different management options of the farmer, we assume that the farmer is a risk-averse decision maker. In order to control for 'profit maximizing' decision makers, we include the analysis of a risk-neutral farmer that faces the following optimization problem that maximizes the expected quasi rents (e.g., Hardaker et al. 1997):

$$\max_{N,D} E(\pi) = E(Y(N))P - cN + D \cdot \mathrm{DP} \tag{1}$$

$E(\pi)$ denotes the expected value of quasi rents (revenue minus variable costs), other costs are assumed to be fixed and thus irrelevant for the here considered decision making context. P denotes the price for grassland yield (i.e., hay), N is the amount of nitrogen employed, $E(Y(N))$ is the expected grassland yield that depends on the fertilizer amount N, c is the price of nitrogen and DP denote the amount of direct payments (nonrandom annual payments). D is an indicator function for the adoption of direct payments, showing that we analyze two options, one without direct payments and an option that includes general direct payments of $\mathrm{DP} = 1{,}040$ CHF ha^{-1} per year. Thus, the risk-neutral farmer maximizes his quasi rents with respect to nitrogen use and the adoption of direct payments. More than 90% of the Swiss farmers receive these general direct payments and are thus integrated in a cross-compliance scheme (BLW 2008). In order to receive general direct payments, farmers must satisfy the conditions of the so-called *Ökologischer Leistungsnachweis* (proof of compliance with ecological requirements) (Mann 2003). These obligations are intended to protect soils and prevent excess in the fertilizer balance. To prevent nutrient losses caused by excessive fertilizer application, the application of fertilizer is restricted to the nutrient requirements of the plants. For intensively managed grasslands, nitrogen application is restricted at 12 kg N per 1 t of grassland yield (BLW 2006).[2] Price levels are taken from the internet database *agrigate.ch* operated by the Swiss Farmers' Union (SBV) and the Swiss Association for the Development of Agriculture and Rural Areas (AGRIDEA). The output price is equal to $P = 150$ CHF t^{-1}, assuming hay to be sold directly from the swath, with a high dry matter content requiring no further ventilation. Ammonium nitrate with a nitrogen content of 27.5% is assumed for grassland fertilization with a price of 0.65 CHF kg^{-1}, which is equivalent to 2.36 CHF kg^{-1} for pure nitrogen.

Calculation of certainty equivalents

For the risk-neutral farmer, the optimal production intensity does not depend on the variability or skewness of yields and thus profits. In contrast, these higher moments of the yield distribution are taken into account in the framework of a risk-averse farmer. Note that the here presented analysis focuses on production risks and does not account for price risks. The here presented framework of certainty equivalent maximization for a risk-averse decision maker is taken from Di Falco and Chavas (2006), who also provide a detailed description and discussion of the power utility function underlying the here presented analysis. The certainty equivalent is a monetary measure which is the nonrandom (i.e., sure) amount of income that gives the (risk averse) farmer the same utility as a higher but random income and can be defined as follows:

$$\mathrm{CE} = E(\pi) - \mathrm{RP} \tag{2}$$

where CE denotes the certainty equivalent and RP is the risk premium, i.e., the amount of money the decision maker is willing to pay to replace the uncertain quasi rent π by its mean $E(\pi)$. $\mathrm{RP} < 0$, $\mathrm{RP} = 0$, and $\mathrm{RP} > 0$ denote a risk-loving, risk-neutral and risk-averse decision maker, respectively. The risk premium depends on the risk preferences and the distribution of quasi rents. Following Di Falco and Chavas (2006), we define the (approximate) risk premium in our analysis as follows (see Antle 1987, for a description of this moment-based approach):

$$\mathrm{RP} = \frac{1}{2} r_2 M_2 + \frac{1}{6} r_3 M_3 \tag{3}$$

M_i is the ith central moment of the distribution of quasi rents and r_2 is the coefficient of risk aversion. If $r_2 > 0$ (i.e., the farmer is risk averse), an increase in the variance of quasi rents (i.e., M_2) increases the risk premium, and decreases the certainty equivalent. r_3 describes the aversion against downside risk, i.e., the (negative) skewness of quasi rents (M_3). If $r_3 < 0$, an increase in the negative skewness (i.e., an increasing risk of facing "low-income" outcomes, Chavas et al. 2010) of quasi rents increases the risk premium and decreases the certainty equivalent of the farmer.

The first, second, and third moments of quasi-rent distributions are estimated with the mean, variance, and (unstandardized) skewness of the quasi rents. We assume constant relative risk aversion, which corresponds to decreasing absolute risk aversion with $r_2 = 2/E(\pi)$ and $r_3 = -6/\sigma^2(\pi)$. These levels (and forms) of risk aversion

[2] In practice, farmers are required to show an equalized fertilizer balance at their farm, where nitrogen needs for intensive grasslands are calculated using the factor given above. Nitrogen applications above this level increase the risks of nutrient losses to the environment and are thus not allowed. Due to unforeseen (e.g. weather) events, this critical value can be exceeded within a range of tolerance.

reflect frequently observed[3] risk preferences with a moderate risk aversion of the farmer (Di Falco and Chavas 2006). This choice of farmers' risk preferences assumes that the level of risk aversion decreases with increasing level of quasi rents. Moreover, downside risk aversion is assumed to decrease with increasing variance of quasi rents.

Insurance application

To illustrate a potential insurance application, we use the example of farm-level yield insurance based on the actual production history of the farm (see Bielza et al. 2008, for an overview on global applications). Such insurance assumes a "guaranteed" yield, based on farm-level yield history. The insurance is evaluated at the price level P. We assume a coverage level of 90% (i.e., a deductible of 10%). Thus, if the actual crop yield (Y_i) falls below the 90th percentile of average yields ($\bar{Y}$), the farmer is indemnified. This yield level is the 'trigger' or 'critical' yield (Barnett et al. 2005), $Y^C = 0.9\,\bar{Y}$. Thus, the indemnity payment function can be described as follows:

$$\text{Indemnity} = \max\{0, Y^C - Y_i\} \cdot P. \tag{4}$$

The premium of the insurance is calculated based on the observed variability of crop yields[4] and is equal to the expected indemnity payment times a loading factor of 1.3 (e.g., for administrative costs, generating profits and accumulation of reserves). Thus, we assume that the insurance premium is 30% higher than the 'fair premium' that is equal to the expected indemnity payment. We use nonparametric bootstrap to derive unbiased estimates of expected indemnity payments. Insurance premiums are calculated for specific levels of nitrogen application, because different fertilizer use implies different production risks. Thus, we assume that the farmer chooses the technology (level of N) if he contracts the insurance.[5] In the absence of an agreement on the production technology used by the farmer, such insurance would imply problems of moral hazard and adverse selection.

Therefore, we assume the farmer to maximize his certainty equivalents with respect to (a) the level of nitrogen application (N), (b) the use of an insurance (I), where I is an indicator function indicating the use of insurance (c) the inclusion in the cross-compliance scheme (i.e., production restrictions) that implies the receipt of direct payments (D). These three variables determine the mean ($E(\pi(N, I, D))$), the variance ($\sigma^2(\pi(N, I, D))$), and the skewness ($\sigma^3(\pi(N, I, D))$) of quasi rents and are thus included in the final certainty equivalent maximization problem of our analysis that can be formulated as follows:

$$\max_{N,I,D} \text{CE} = E(\pi(N,I,D)) - \frac{1}{2} r_2 \sigma^2(\pi(N,I,D)) + \frac{1}{6} r_3 \sigma^3(\pi(N,I,D)). \tag{5}$$

To analyze the sensitivity of our analysis with regard to the employed parameters in the economic model, we conduct a sensitivity analysis taking different levels of risk aversion, loading factors, and direct payments into account.

In order to assess the reliability of the here calculated point estimates for quasi rents and certainty equivalents, we construct 95% confidence intervals of these estimates using nonparametric bootstrap (see DiCiccio and Efron 1996, for details). To this end, the above described values are estimated for 9,999 data replicates that are generated by sampling with replacement from each dataset. Furthermore, we use these confidence intervals to test for significant differences between different levels of nitrogen application as well as between climate scenarios, though we are aware that the comparison of confidence intervals is a very conservative way of hypothesis testing (Schenker and Gentleman 2001). All statistical and graphical analysis presented in this paper are conducted with the statistical language and environment R (R Development Core Team 2008).

Results

Generated yield data

The simulated grassland yield data (i.e., the output of the simulations with PROGRASS) are summarized in Table 2. In this paper, grassland yield is defined as the sum of clover and grass dry matter yields (i.e., above-ground biomass). For the BASE scenario, it shows that grassland yield increases with increasing nitrogen application (N), however, with decreasing marginal productivity. The standard deviation (SD) nearly continuously increases with increasing N, while the minimum coefficient of variation (CV) is reached at 200 kg N ha^{-1} year^{-1}. Moreover, we find a contrary effect of nitrogen application on the skewness of grassland yields. The negative skewness of grassland yields increases till 200 kg N ha^{-1} year^{-1}, but decreases henceforward. Thus, production risks show nonlinear patterns in response to nitrogen application, which is caused by the

[3] No estimates of risk aversion of Swiss farmers are available yet.

[4] This means the 25 simulations for each N-level and climate scenario that presented in Table 1 are used to estimate insurance premiums. Thus, we assume that yield variability is known to both the insurer and the insurant.

[5] Such an agreement on a specific technology can be (partially) controlled if farmers are required to submit field management handbooks (records) to the insurance company, which is e.g. applied by the Saskatchewan crop insurance (http://www.saskcropinsurance.com, accessed March 07, 2011).

Table 2 Descriptive analysis of simulated grassland yields

N (kg ha^{-1})	BASE scenario					Climate-change scenario				
	Mean (t ha^{-1})	SD (t ha^{-1})	CV	(stand.) Skewn.	Kg *N*/mean yield	Mean (t ha^{-1})	SD (t ha^{-1})	CV	(stand.) Skewn.	Kg *N*/mean yield
50	8.82	1.31	0.15	−0.77	5.67	10.92	2.13	0.19	0.54	4.58
100	10.05	1.37	0.14	−0.85	9.95	11.63	2.15	0.19	0.52	8.60
150	10.88	1.31	0.12	−1.16	13.79	12.15	2.20	0.18	0.67	12.35
200	12.10	1.44	0.12	−1.25	16.53	12.98	2.10	0.16	0.45	15.41
250	13.27	1.62	0.12	−1.24	18.84	14.14	2.25	0.16	0.34	17.68
300	14.29	1.81	0.13	−1.20	20.99	15.26	2.46	0.16	0.32	19.66
350	15.14	1.98	0.13	−1.16	23.12	16.28	2.68	0.16	0.32	21.50
400	15.84	2.13	0.13	−1.12	25.25	17.17	2.88	0.17	0.34	23.30
450	16.41	2.26	0.14	−1.10	27.42	17.94	3.08	0.17	0.37	25.08
500	16.88	2.37	0.14	−1.08	29.62	18.60	3.25	0.17	0.39	26.88

interaction between clover and grass in the here analyzed grassland system and their different responses to heat and temperature stress as well as nitrogen application (see Lazzarotto et al. 2009, for details). In particular, the clover fraction decreases with increasing levels of nitrogen application, which reflects enhanced competitive advantages of the grass under high N application, both with respect to light interception (Hautier et al. 2009) as well as soil mineral N acquisition (Lazzarotto et al. 2009).

For the climate-change scenario, Table 2 shows that grassland yields are higher than for current climatic conditions, particularly due to the benefits of rising atmospheric CO_2 concentrations. These yield increases range between 10% ($N = 500$ kg ha^{-1}) and 24% (for $N = 50$ kg ha^{-1}). This yield increase is in agreement with findings from previous studies (e.g., Nijs et al. 1996; Riedo et al. 1999). However, Table 2 shows furthermore that the rise in mean yields is associated with a sharp increase in the standard deviation of grassland yields and increasing coefficients of variation. The climate change induced increases of the coefficients of variation range between 21% (e.g., for $N = 500$ kg ha^{-1}) and 50% (for $N = 150$ kg ha^{-1}). These results indicate that climate change increases production risks. However, we find a shift in the skewness of yields, from negatively skewed yields under current to positively skewed yields under future climatic conditions. In order to validate the observed shifts in mean, dispersion and skewness of grassland yields, we also considered robust methods[6] that lead to similar results.

The observed increase in mean yields due to climate change is positive for farmers. Ceteris paribus, also the positive shift in skewness is beneficial for farmers because the frequency of low-yield events is reduced. However, the here found joint occurrence of this shift with an increasing variance of yields is ambiguous for the farmers utility. To (jointly) evaluate and quantify these effects, the certainty equivalents are used (cp. Eq. 5). In summary, our descriptive analysis of grassland yields shows that farmers will benefit particularly from an increasing mean of grassland yields, but suffer from much higher yield variability. A detailed description and discussion of the here used dataset is given in Finger et al. (2010).

Table 3 Insurance premiums (in CHF ha^{-1}) for the BASE and the climate-change scenario

N (kg ha^{-1})	BASE	Climate change
50	45.20	67.77
100	43.85	65.60
150	40.53	61.03
200	45.68	52.41
250	53.07	56.26
300	60.43	62.40
350	67.39	70.11
400	73.81	77.52
450	79.29	84.50
500	83.97	90.85

Estimated insurance premiums

Table 3 shows the calculated insurance premiums (IP) that are equal to the expected indemnity payment (i.e., the expected values below the trigger yield, evaluated at the grassland price of 150 CHF t^{-1}) times a loading factor of 1.3. Thus, these insurance premiums reflect the actual risk that yields fall below the trigger yield, which is defined as the 90th percentile of the expected (i.e., average) yield. This risk (and thus the premium) varies with the level of

[6] Robust methods to estimate the location, dispersion and skewness of the yield distributions were the median, the Qn and the medcouple estimator, respectively (see Brys et al. 2003, for details).

Table 4 Descriptive statistics of quasi rents (in CHF ha^{-1}) for the BASE scenario

N (kg ha^{-1})	Without insurance				With insurance			
	Mean (CHF ha^{-1})	SD (CHF ha^{-1})	CV (–)	Skewness (–)	Mean (CHF ha^{-1})	SD (CHF ha^{-1})	CV (–)	Skewness (–)
w/o direct payment								
50	1,204.41	196.93	0.16	−0.77	1,193.98	137.59	0.12	0.08
100	1,270.97	205.79	0.16	−0.85	1,260.85	145.39	0.12	0.08
150	1,278.14	195.77	0.15	−1.16	268.79	133.21	0.10	−0.10
200	1,342.75	215.74	0.16	−1.25	1,332.21	143.91	0.11	−0.18
250	1,401.09	243.62	0.17	−1.24	1,388.84	161.23	0.12	−0.15
300	1,435.95	271.26	0.19	−1.20	1,422.01	179.19	0.13	−0.10
350	1,445.11	296.95	0.21	−1.16	1,429.56	196.10	0.14	−0.04
400	1,431.35	319.96	0.22	−1.12	1,414.32	211.15	0.15	0.02
450	1,399.12	339.45	0.24	−1.10	1,380.83	223.84	0.16	0.05
500	1,352.35	355.84	0.26	−1.08	1,332.97	234.34	0.18	0.08
With direct payment								
50	2,244.41	196.93	0.09	−0.77	2,233.98	137.59	0.06	0.08
100	2,310.97	205.79	0.09	−0.85	2,300.85	145.39	0.06	0.08
150	*2,318.14*	*195.77*	*0.08*	*−1.16*	*2,308.79*	*133.21*	*0.06*	*−0.10*
200	*2,382.75*	*215.74*	*0.09*	*−1.25*	*2,372.21*	*143.91*	*0.06*	*−0.18*
250	*2,441.09*	*243.62*	*0.10*	*−1.24*	*2,428.84*	*161.23*	*0.07*	*−0.15*
300	*2,475.95*	*271.26*	*0.11*	*−1.20*	*2,462.01*	*179.19*	*0.07*	*−0.10*
350	*2,485.11*	*296.95*	*0.12*	*−1.16*	*2,469.56*	*196.10*	*0.08*	*−0.04*
400	*2,471.35*	*319.96*	*0.13*	*−1.12*	*2,454.32*	*211.15*	*0.09*	*0.02*
450	*2,439.12*	*339.45*	*0.14*	*−1.10*	*2,420.83*	*223.84*	*0.09*	*0.05*
500	*2,392.35*	*355.84*	*0.15*	*−1.08*	*2,372.97*	*234.34*	*0.10*	*0.08*

Alternatives in italic indicate non-feasible solutions under the cross-compliance scheme (i.e., a restriction on nitrogen use)

nitrogen application and with the climate scenario. It shows that premiums for current climatic conditions are lowest for $N = 150$ kg ha^{-1}.

For the climate-change scenario, insurance premiums are higher than for the BASE scenario with the lowest premium for $N = 200$ kg ha^{-1}. However, the increase in premiums from current to future climate is small compared with the large increase in the standard deviation of yields for the climate-change scenario (cp. Table 2), particularly due to the shift toward more positively skewed yields.

Results for quasi rents

Table 4 shows descriptive statistics of the distributions of quasi rents under current climate conditions for: (1) situations without insurance and direct payments ($\pi = Y(N) \cdot 150 - 2.36 \cdot N$), (2) only with insurance ($\pi = Y(N, I) \cdot 150 - 2.36 \cdot N - \mathrm{IP}(N)$), where $Y(I)$ is the insured yield (i.e., yield distributions are truncated below the trigger yield), (3) with direct payments only ($\pi = Y(N) \cdot 150 - 2.36 \cdot N + \mathrm{DP}$), and (4) accounting for both insurance and direct payments ($\pi = Y(N, I) \cdot 150 - 2.36 \cdot N - \mathrm{IP}(N) + \mathrm{DP}$).

Table 4 illustrates that the application of insurance has three intuitive effects on the distribution of quasi rents: (1) it decreases the mean quasi rent (because insurance premiums exceed the indemnity payments), (2) it decreases the variability (standard deviation) of quasi rents and (3) removes a large part of negative skewness from the quasi rents (i.e., quasi rents are more positively skewed).

The lower panel of Table 4 shows that direct payments significantly increase the mean income levels (confidence intervals are presented in the "Appendix"). Moreover, direct payments have also a risk decreasing (i.e., insurance like) effect by increasing the expected quasi rent while keeping the standard deviation unaffected. Thus, direct payments lead to much lower coefficients of variation.

Taking both insurance and direct payments into account, our analysis shows that the relative variability (CV) of quasi rents decreases in the range of a factor 2–3. For instance, the coefficient of variation of quasi rents under current climate for $N = 200$ kg ha^{-1} without direct payments and without insurance is equal to 0.16. The insurance and receipt of direct payment reduce the coefficient of variation to 0.11 and 0.09, respectively. With both

Table 5 Descriptive Statistics of quasi rents (in CHF ha^{-1}) for the climate-change scenario

N (kg ha^{-1})	Without insurance				With insurance			
	Mean (CHF ha^{-1})	SD (CHF ha^{-1})	CV (–)	Skewness (–)	Mean (CHF ha^{-1})	SD (CHF ha^{-1})	CV (–)	Skewness (–)
w/o direct payment								
50	1,520.19	318.98	0.21	0.54	1,504.55	258.56	0.17	1.34
100	1,508.81	322.99	0.21	0.52	1,493.68	264.13	0.18	1.29
150	1,468.47	330.28	0.22	0.67	1,454.39	277.86	0.19	1.34
200	1,474.80	314.53	0.21	0.45	1,462.71	264.80	0.18	1.12
250	1,530.74	337.14	0.22	0.34	1,517.75	282.30	0.19	1.01
300	1,581.48	369.02	0.23	0.32	1,567.08	308.11	0.20	0.98
350	1,615.48	401.29	0.25	0.32	1,599.30	333.69	0.21	0.99
400	1,631.02	432.21	0.26	0.34	1,613.13	358.42	0.22	1.01
450	1,628.75	461.39	0.28	0.37	1,609.25	381.92	0.24	1.04
500	1,610.33	487.73	0.30	0.39	1,589.37	403.29	0.25	1.07
With direct payment								
50	2,560.19	318.98	0.12	0.54	2,544.55	258.56	0.10	1.34
100	2,548.81	322.99	0.13	0.52	2,533.68	264.13	0.10	1.29
150	*2,508.47*	*330.28*	*0.13*	*0.67*	*2,494.39*	*277.86*	*0.11*	*1.34*
200	*2,514.80*	*314.53*	*0.13*	*0.45*	*2,502.71*	*264.80*	*0.11*	*1.12*
250	*2,570.74*	*337.14*	*0.13*	*0.34*	*2,557.75*	*282.30*	*0.11*	*1.01*
300	*2,621.48*	*369.02*	*0.14*	*0.32*	*2,607.08*	*308.11*	*0.12*	*0.98*
350	*2,655.48*	*401.29*	*0.15*	*0.32*	*2,639.30*	*333.69*	*0.13*	*0.99*
400	*2,671.02*	*432.21*	*0.16*	*0.34*	*2,653.13*	*358.42*	*0.14*	*1.01*
450	*2,668.75*	*461.39*	*0.17*	*0.37*	*2,649.25*	*381.92*	*0.14*	*1.04*
500	*2,650.33*	*487.73*	*0.18*	*0.39*	*2,629.37*	*403.29*	*0.15*	*1.07*

Alternatives in italic indicate nonfeasible solutions under the cross-compliance scheme (i.e., a restriction on nitrogen use)

insurance and direct payment, the coefficient of variation of quasi rents for $N = 200$ kg ha^{-1} reduces to 0.06.

Table 5 shows the descriptive statistics of the distributions of quasi rents under future climatic conditions. We find that climate change increases quasi rents (due to yield increases) but leads to over-proportional increases in the variability. Thus, coefficients of variation of quasi rents for the climate-change scenario are higher than for the BASE scenario. With respect to the effects of direct payments and insurance, similar effects as described for current climate are observed. In summary, we find higher grassland production risks in future, but both direct payments and insurance seem to be potentially powerful tools to reduce these risks.

Results for certainty equivalents

In order to evaluate the different alternatives (under different climate regimes) for a risk-averse farmer, the quasi rents described in Tables 4 and 5 are used to assess the respective certainty equivalents (Eq. 5) of these alternatives. The results for quasi rents and certainty equivalents (with and without insurance) are summarized in Fig. 1. The exact estimates and confidence intervals are presented in the "Appendix".

For the BASE scenario, Fig. 1a shows that the relationship between nitrogen and profits as well as certainty equivalents is inverse U-shaped. Increasing nitrogen application leads to increasing marginal quasi rents (and certainty equivalents), which decrease after a maximum has been reached. It shows that the risk premium (i.e., the difference between mean quasi rents and certainty equivalents) increases with nitrogen application, particularly because nitrogen increases the variance of grassland yields. For the risk-neutral farmer, the optimal amount of nitrogen that maximizes expected profits is equal to 350 kg ha^{-1}. In contrast, a risk-averse farmer would maximize certainty equivalents with 300 kg ha^{-1}. Because nitrogen is a risk increasing input, risk aversion reduces the incentives to use this input. It shows that if there is the possibility to use a farm-level yield insurance, the risk-averse farmer would produce more intensively using a nitrogen application of $N = 350$ kg ha^{-1}. Thus, the presence of an insurance scheme increases the incentive to intensify grassland

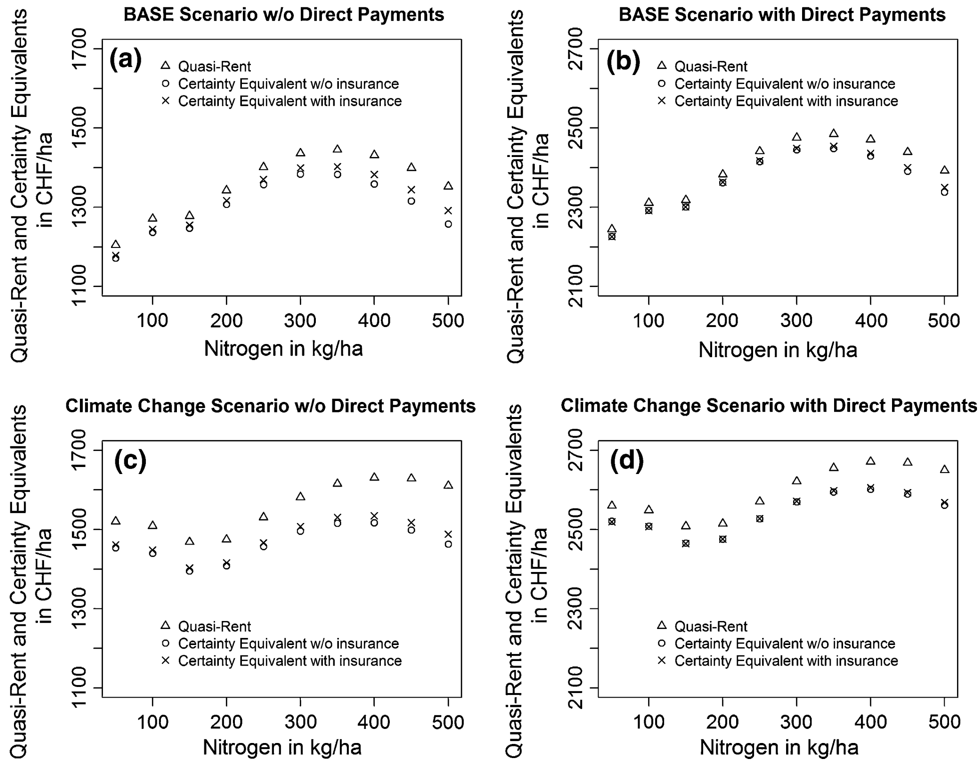

Fig. 1 Profits and certainty equivalents (in CHF ha^{-1}) for the BASE and the climate-change scenario. *Note* that the results displayed in this figure assume a constant relative risk aversion of $r_2 = 2/E(\pi)$ and a downside risk aversion of $r_3 = -6/\sigma^2(\pi)$ (cp. "Calculation of certainty equivalents")

production (and making it more risky) by using more nitrogen. Note that even though the differences in certainty equivalents between the here considered levels of nitrogen are small (and not significant), these results indicate the expected effects of considering risk aversion and the presence of insurance possibilities. Our results show that farmers would use the farm-level yield insurance because certainty equivalents in the BASE scenario (without direct payments) for the insurance option are always higher than for the noninsured alternative.

Figure 1b shows the results for the BASE scenario with consideration of direct payments. It shows that direct payments lead to significantly higher expected profits for risk neutral, as well as to significantly higher certainty equivalents for risk-averse farmers (with and without insurance option) than for the option without direct payments. Due to the cross-compliance requirements (12 kg N per 1 t of grassland yield), the farmer has a constraint maximization problem. Only the application levels of 50 and 100 kg ha^{-1} fulfill this requirement (cp. Table 2) and thus $N_{max} = 100$ kg ha^{-1}(cp. Table 2). Consequently, the risk-neutral farmer maximizes expected profits including direct payments with $N = 100$ kg ha^{-1}. Because this (constrained) optimum leads to higher profits than the unconstrained optimization, the farmer will choose the first option that includes the receipt of direct payments. Because the same holds for the risk-averse decision maker, we conclude that direct payments and the according cross-compliance scheme are always adopted in the here considered example, which is in line with high participation rates in the cross-compliance scheme observed in Switzerland.

Figure 1b shows furthermore that direct payments reduce the incentives to adopt farm-level yield insurance. Direct payments have an insurance effect itself (reducing the relative variability of quasi rents) and reduce the (absolute) risk aversion of the farmer (by shifting his welfare level upwards). Hennessy (1998) provides detailed descriptions and proofs of the insurance and wealth effects of direct payments.[7] Therefore, comparing Fig. 1a, b, the relative risk premium (defined as $RP/E(\pi)$[8]) that accounts for direct payments is much smaller than without considerations of direct payments. Moreover, the (relative) difference between certainty equivalents with and without insurance contract decreases sharply.

[7] Femenia et al. (2010) summarize and revisit the discussion on the existence of this "wealth effect" of direct payments.

[8] The risk premium RP is defined as the difference between quasi-rents and certainty equivalents.

In summary, under current climatic conditions (BASE scenario), farmers in our example are expected to adopt direct payments, use the most intensive production alternative that is allowed in the cross-compliance scheme ($N = 100$ kg ha^{-1}), and will not use the farm-level yield insurance. Because the adoption of the insurance depends strongly on the assumed risk aversion as well as the assumed loading factor, both will be subject of sensitivity analysis presented at the end of this section.

Figure 1c shows quasi rents and certainty equivalents (with and without insurance) for the climate-change scenario. We find that quasi rents and certainty equivalents are higher than in the base scenario due to higher yield levels.[9] For the climate-change scenario, Fig. 1c shows that the relationship between nitrogen and profits as well as certainty equivalents is not strictly inverse U-shaped. An increasing nitrogen application from 50 to 150 kg ha^{-1} leads—surprisingly—to decreasing marginal profits and certainty equivalents. Thus, the additional nitrogen fertilizer is more expensive than the gains from higher yield levels. This response can be explained by the interactions between grass and clover considered in the PROGRASS model. The clover fraction responds markedly to elevated CO_2 concentrations, as the latter stimulates photosynthesis in clover more than grass and has also positive effects on symbiotic N fixation (Hebeisen et al. 1997). Even though the changes in climatic conditions, ceteris paribus, reduce the competitiveness of clover compared with grass (because it is less tolerant to water stress), the overall effect for clover in the climate-change scenario is positive (Lazzarotto et al. 2009; Finger et al. 2010). Because of high biological N fixation rates (due to the high clover content), yields are already on a high level even without nitrogen fertilizer application. Thus, additional nitrogen application (that increases grass yield but reduces the clover content) has only a small marginal productivity, i.e., leads only to small total grassland yield increases. Consequently, profits and certainty equivalents decrease with nitrogen application until reaching a minimum at $N = 150$ kg ha^{-1}, and increase again until the (global) maximum is reached for $N = 400$ kg ha^{-1}, which is the optimal nitrogen amount for the farmer. This result shows that climate change induces an increase in the production intensity (from 350 to 400 kg ha^{-1}) in an unconstrained optimization problem.

Figure 1c shows furthermore that the relative risk premium (i.e., the difference between quasi rents and certainty equivalents, divided by the mean quasi rent) increases with climate change due the sharp increase in the dispersion of quasi rents (cp. Table 4). The benefits of the farm-level yield insurance and direct payments remain as for the BASE scenario: risk-averse farmers would use the insurance; but direct payments reduce the incentives to adopt farm-level yield insurance (i.e., the insurance is not used). Because direct payments lead again to significantly higher certainty equivalents, we assume that farmers will adopt the required cross-compliance obligations also under future climatic conditions. The obligations imply a counter-intuitive effect of climate change on the production intensity: Taking direct payments into account, farmers maximize certainty equivalents with $N = 50$ kg ha^{-1}, i.e., they produce less intensive.

Thus, the effect of climate change on grassland production intensities is ambiguous: it increases optimal fertilizer use in unconstrained production conditions but decreases optimal fertilizer use in the presence of cross-compliance obligations. This effect is caused by the climate change–induced changes in grass-clover competition that have been discussed above.

In summary, we find that under future climatic conditions, farmers will adopt direct payments, use low-intensity production ($N = 50$ kg ha^{-1}), and will not use the farm-level yield insurance.

Results of the sensitivity analyses

In order to analyze the sensitivity of the results with regard to the employed parameters in the economic model, we recalculate the gains in certainty equivalents from having farm-level yield insurance (i.e., the percentage increase of certainty equivalents due to the participation in the insurance scheme) for different levels of risk aversion and loading factors. Moreover, we consider three levels of direct payments with 1,040, 693 and 347 CHF ha^{-1}, representing 100, 66 and 33% of current direct payments, respectively. Concerning the coefficient of constant relative risk aversion, we use levels from -1 (risk loving), 0 (risk neutral), 1, 2, 3, and 4 (all risk averse). These 6 levels of constant relative risk aversion are combined (in this order) with different levels of downside risk aversion: $+1$ (loving downside risk), 0 (neutral with respect to downside risk), -3, -6, -9, and -12 (all averse to downside risk), respectively. The consideration of risk-loving behavior is motivated by the findings of Koundouri et al. (2009) for Finnish farmers. High values of risk aversion represent rather exceptionally high risk aversion (see Gardeboek 2006, for an overview on empirical results for coefficients of constant relative risk aversion). In this sensitivity analysis, we also consider 4 levels of loading factors: 0.4 (extremely subsidized insurance), 0.7 (highly subsidized

[9] Significant increases for quasi rents are in particular indicated for low levels of nitrogen application ($N = 50$ and 100 kg ha^{-1}, cp. "Appendix").

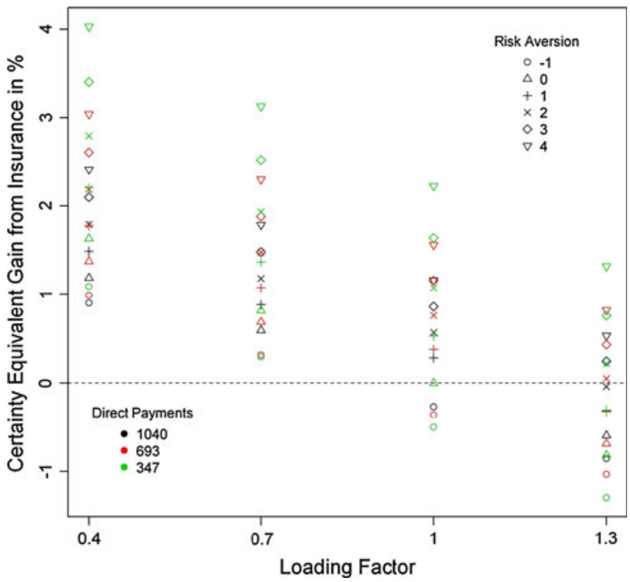

Fig. 2 Sensitivity analysis: relative certainty equivalent gains from insurance for different rates of risk aversion, loading factors, and direct payments. *Note* that for the case of a fair premium (loading factor = 1), the certainty equivalent gain from insurance for a risk-neutral decision maker is zero, irrespectively from direct payments. Thus, the respective points in Fig. 2 overlap

insurance), 1 (moderately subsidized insurance, leading to a 'fair premium') and 1.3 (unsubsidized insurance, considering costs of the insurance company). While the loading factor of 1.3 might reflect the real costs (and premiums) of an insurer under free market conditions, lower values incorporate different degrees of (governmental) subsidies for the considered farm-level yield insurance. Current subsidies for insurance premiums in Europe range from 0% to about 75% (Bielza et al. 2008). Results for the sensitivity analysis are shown in Fig. 2. Because the results for the BASE scenario lead to qualitatively similar results, we display the results for the climate-change scenario only. It shows that for risk-averse farmers, higher direct payments lead to lower gains from the insurance due to the insurance and wealth effects of direct payments. Subsidies for the insurance premiums increase the gains from insurances for all farmers. Moreover, it shows that higher risk aversion leads to higher gains from the insurance. For high rates of subsidies for the insurance premiums (i.e., the loading factors of 0.4 and 0.7), insurance is even profitable for risk-neutral and risk-loving farmers. In contrast, a fair insurance premium (loading factor equal to 1) makes insurance unattractive for risk-loving farmers and makes risk-neutral farmers indifferent between adoption and nonadoption of the insurance. Without subsidies on premiums (loading factor equal to 1.3), only farmers with moderate and high risk aversion would use the insurance.

For the specific case of risk aversion being equal to 2 and loading factor equal to 1.3, it shows that direct payments trigger the adoption of farm-level yield insurance (i.e., direct payments lead to nonadoption of the insurance). With regard to the loading factors of insurance premiums, our results are in line with the findings of Just et al. (1999) that insurance subsidies might be more important for the decision to participate in an insurance scheme than the risk aversion of the farmer. Thus, our results suggest that there is a large policy influence on the choice of a specific risk management measure to cope with climate change–induced production risks in grassland production.

Discussion

Our analysis of climate-change impacts and adaptation in grassland production was limited to a case study referring to a specific grass-clover system, having the Swiss Plateau as geographic focus, and considering only one emission and climate-change scenario. Thus, the results cannot provide the basis for general conclusions. Specifically, there can be objections concerning the choice of a single emission and climate-change scenario. In general, consideration of a full basket of future pathways is necessary to quantify uncertainties and therefore put specific impact assessments into a broader context. More specifically, the use of multiple scenarios would have permitted us to draw conclusions on a more general basis. We opted for the A2 emission scenario and one specific set of climate simulations (the PRUDENCE runs with the CHRM model) as we wanted to set up an illustrative case study that envisages substantial changes in the future climate conditions, providing means to better size the implications for adaptation at the regional scale (cp. Table 1). An important aspect of the scenario development was the application of the stochastic weather generator LARS-WG to obtain unbiased daily and (after further post-processing) hourly weather data. As noted in Orlandini et al. (2008), one of the main difficulties encountered in working directly with the output of global or regional climate models is their insufficient spatial resolution and the existence of systematic biases in key meteorological fields. In particular, current modeling systems show a tendency to overestimate the number of rainy days but underestimate rainfall intensity (Frei et al. 2003). Although there are specific correction procedures for improving modeled precipitation (e.g., Schmidli et al. 2006; Rivington et al. 2008), the use of weather generators is a common approach to ensure consistency between the different meteorological variables (e.g., Hansen et al. 2006). As discussed in

Lazzarotto et al. (2010), the specific weather generator adopted for the present study proved to work satisfactorily for our study site.

In our analysis, expected adaptation responses were analyzed from the farmers' perspective, i.e., we investigated what adjustments are expected to be made by the farmer in response to climate change. In order to derive optimal adaptation responses from the policy makers' (or societal) perspective, other goal functions have to be employed that account for climate change mitigation and nature conservation (e.g., Holzkämper et al. 2010). A comparison of optimal responses from different perspectives can show in which field policy actions are required to support sustainable adaptation to climate change. Note that the here presented optimization problem for the farmer did not account for tactical decisions, i.e., management adjustments due to specific weather conditions within a growing season were not considered. The here derived optimal management decisions rather reflect average decisions taken by the farmer. Thus, our analysis considered only strategic adjustments of the production intensity and the use of insurance. The integration of tactical (e.g., daily) decisions of farmers in bio-economic modeling approaches is a task for further research (e.g., Antle et al. 2004).

Summary and conclusion

In this paper, we assess climate-change impacts on an intensively managed grass/clover system at the Swiss Plateau using simulated field experiments for 10 different levels of nitrogen application. To this end, we employ the process-based grassland model PROGRASS that accounts for above- and below-ground processes in plant and soil as well as for the interactions between grass and clover. Taking the CO_2 fertilization effect into account, it shows that grasslands yields increase in future. However, this yield increase is accompanied by a sharp increase in yield variability. Thus, climate change increases yield levels but also increases production risks in grassland production.

We show that the dynamics and interactions of grass and clover are essential for the vulnerability of the grassland system to climatic stress and its response to fertilizer application. Our results suggest that the analysis of risks in grassland production requires models that take these dynamics into account. Thus, bio-economic modeling can be enhanced by taking the complexity of the processes in agro-ecosystems explicitly into account. Furthermore, the use of process-based models for the analysis and measurement of grassland production risks (e.g., for an insurance) might re-solve problems of low data availability for grassland production (i.e., a lack of farm production records).

In order to economically evaluate the results from simulated field trials, quasi rents (revenue minus variable costs) are used to calculate certainty equivalents for different levels of nitrogen application. To identify potential risk management strategies, we consider a farm-level yield insurance under current and future climatic conditions. In this insurance scheme, the farmer is indemnified if his actual yield falls below the 90th percentile of his expected (i.e., average) yield. Moreover, we consider direct payments and their role on farmers' decision making by accounting for their wealth and insurance effect as well as related cross-compliance requirements. In the economic decision model, we assume that risk-averse farmers maximize certainty equivalents with respect to the level of nitrogen application, the adoption of insurance and the inclusion in the cross-compliance scheme (that implies the receipt of direct payments).

It shows that farm-level yield insurance reduces the variability of quasi rents and leads to more positively skewed distributions of quasi rents, i.e. reduces the risk of facing low-income outcomes. Thus, farm-level yield insurance is a powerful tool to manage current and future climate risks in grassland production. The here considered unsubsidized insurance (not accounting for direct payments) would be adopted by a moderate risk-averse farmer under current and future climatic conditions. However, direct payments reduce farmers' benefits from insurance. This is due to the assumption that the receipt of direct payments induces an insurance effect, i.e., reduces the relative variability of quasi rents, and induces a wealth effect, i.e., reduces his risk aversion.

A sensitivity analysis that considers different levels of risk aversion, direct payments, and subsidies to the insurance premiums (i.e., loading factors) showed that higher risk aversion increases the benefits from insurance. It showed furthermore that the premium subsidy plays a substantial role in insurance adoption. Under highly subsidized insurance premiums, even risk-loving farmers would adopt insurance, while unsubsidized insurance would be adopted only by highly risk-averse decision makers. Thus, insurance subsidization might induce free-riding effects because expected returns are higher than the premiums paid, making the insurance to a governmental transfer instrument. In order to use, in general, insurance as risk management measure only, governmental subsidies should be moderate.

In order to cope with climate change–induced risk increases, the support for insurance schemes has clear advantages over subsidies for other risk management tools. Farm-level yield insurance is a management option against all possible natural sources of risk, expanding the scope of currently used elementary risk insurance. In particular, this farm yield insurance covers also yield reductions due to water shortages and excess precipitation, which are expected to become more frequent in the future. Moreover, insuring grassland yields implies much less environmental harms (in particular in presence of cross-compliance requirements for input use) compared with other risk management strategies such as the widespread adoption of grassland irrigation (e.g., Baldock et al. 2000).

In summary, our results show that grassland yields are expected to increase under future climate conditions, particularly due to increasing CO_2 concentrations. However, we find that grassland production will also become more risky due to climate change. The use of insurances is a powerful tool for farmers to adapt to these increasing risks. Moreover, governmental support for an introduction of additional insurance solutions might thus be a valuable adaptation strategy to cope with climate change at the national scale.

In order to increase the relevance and applicability of insurance solutions for farming practices, further steps may be necessary. To integrate also quality-related risks in grassland production into insurance solutions, further research should address both quantity and quality issues combined in insurance provisions. In addition, further research should consider harvesting risks due to unfavorable weather conditions that might imply additional costs for conservation, e.g., for haymaking, and reduce yield quality. Finally, to overcome costly monitoring as well as problems of moral hazard and adverse selection that are associated with the here analyzed farm-level yield insurance, alternative insurance mechanisms such as weather index and area yield index based instruments should be considered, which has been recently introduced in US pasture, rangeland, and forage insurance schemes.[10]

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Appendix

See Table 6.

Table 6 Exact Results of quasi rents, certainty equivalents and confidence intervals (in CHF ha^{-1}) for the BASE and the climate-change scenario

N (kg ha^{-1})	Without direct payments			With direct payments		
	Quasi rents (CHF ha^{-1})	CE Without insurance (CHF ha^{-1})	CE with insurance (CHF ha^{-1})	Quasi rents (CHF ha^{-1})	CE Without insurance (CHF ha^{-1})	CE with insurance (CHF ha^{-1})
BASE scenario						
50	1,204.41 [1,132, 1,284]	1,171.44 [1,085, 1,262]	1,178.20 [1,123, 1,228]	2,244.41 [2,171, 2,323]	2,226.36 [2,148, 2,309]	2,225.58 [2,173, 2,277]
100	1,270.97 [1,195, 1,353]	1,236.80 [1,147, 1,331]	1,244.16 [1,187, 1,298]	**2,310.97 [2,236, 2,393]**	**2,291.79 [2,207, 2,377]**	**2,291.74 [2,236, 2,346]**
150	1,278.14 [1,209, 1,356]	1,247.00 [1,160, 1,342]	1,254.70 [1,201, 1,305]	*2,318.14 [2,246, 2,397]*	*2,300.45 [2,222, 2,387]*	*2,301.00 [2,249, 2,352]*
200	1,342.75 [1,265, 1,432]	1,306.84 [1,213, 1,414]	1,316.48 [1,259, 1,373]	*2,382.75 [2,305, 2,472]*	*2,361.97 [2,275, 2,457]*	*2,363.30 [2,307, 2,419]*
250	1,401.09 [1,316, 1,499]	1,357.48 [1,247, 1,482]	1,369.97 [1,304, 1,434]	*2,441.09 [2,354, 2,538]*	*2,415.53 [2,315, 2,528]*	*2,417.99 [2,356, 2,481]*
300	1,435.95 [1,339, 1,547]	**1,383.51 [1,261, 1,526]**	1,399.33 [1,327, 1,469]	*2,475.95 [2,379, 2,583]*	*2,445.03 [2,332, 2,570]*	*2,448.87 [2,378, 2,518]*
350	**1,445.11 [1,338, 1,567]**	1,382.93 [1,243, 1,537]	**1,402.62 [1,324, 1,476]**	*2,485.11 [2,377, 2,607]*	*2,448.46 [2,323, 2,590]*	*2,453.95 [2,376, 2,528]*
400	1,431.35 [1,314, 1,564]	1,358.70 [1,210, 1,533]	1,382.81 [1,297, 1,463]	*2,471.35 [2,355, 2,599]*	*2,428.80 [2,293, 2,582]*	*2,436.17 [2,352, 2,516]*
450	1,399.12 [1,275, 1,539]	1,315.67 [1,150, 1,502]	1,344.59 [1,252, 1,430]	*2,439.12 [2,315, 2,579]*	*2,390.79 [2,243, 2,554]*	*2,400.18 [2,313, 2,482]*
500	1,352.35 [1,226, 1,497]	1,257.64 [1,080, 1,461]	1,291.85 [1,196, 1,380]	*2,392.35 [2,266, 2,535]*	*2,338.34 [2,184, 2,512]*	*2,349.91 [2,256, 2,439]*
Climate-change scenario						
50	1,520.192 [1,393, 1,640]	1,453.80 [1,328, 1,566]	1,461.46 [1,409, 1,572]	**2,560.19 [2,435, 2,679]**	**2,520.99 [2,398, 2,636]**	**2,519.62 [2,463, 2,634]**
100	1,508.814 [1,383, 1,631]	1,440.20 [1,312, 1,556]	1,448.26 [1,389, 1,559]	2,548.81 [2,422, 2,672]	2,508.41 [2,382, 2,624]	2,507.43 [2,447, 2,624]

[10] Program details and descriptions are available at the USDA homepage: http://www.rma.usda.gov/policies/pasturerangeforage/, accessed March, 04, 2011.

Table 6 continued

N (kg ha^{-1})	Without direct payments			With direct payments		
	Quasi rents (CHF ha^{-1})	CE Without insurance (CHF ha^{-1})	CE with insurance (CHF ha^{-1})	Quasi rents (CHF ha^{-1})	CE Without insurance (CHF ha^{-1})	CE with insurance (CHF ha^{-1})
150	1,468.469 [1,339, 1,592]	1,394.86 [1,266, 1,508]	1,402.64 [1,344, 1,519]	*2,508.47 [2,378, 2,630]*	*2,465.66 [2,338, 2,578]*	*2,464.78 [2,401, 2,585]*
200	1,474.803 [1,351, 1,596]	1,408.17 [1,285, 1,523]	1,415.89 [1,348, 1,519]	*2,514.80 [2,393, 2,634]*	*2,475.91 [2,355, 2,590]*	*2,475.81 [2,400, 2,587]*
250	1,530.737 [1,400, 1,656]	1,456.83 [1,322, 1,587]	1,466.25 [1,388, 1,575]	*2,570.74 [2,439, 2,698]*	*2,526.87 [2,394, 2,653]*	*2,527.60 [2,445, 2,641]*
300	1,581.483 [1,442, 1,723]	1,495.69 [1,340, 1,638]	1,507.48 [1,420, 1,624]	*2,621.48 [2,478, 2,762]*	*2,569.85 [2,423, 2,705]*	*2,571.65 [2,481, 2,698]*
350	1,615.483 [1,459, 1,766]	1,516.12 [1,350, 1,672]	1,530.67 [1,437, 1,660]	*2,655.48 [2,497, 2,808]*	*2,595.16 [2,436, 2,741]*	*2,598.10 [2,502, 2,731]*
400	**1,631.021 [1,464, 1,795]**	**1,516.83 [1,335, 1,685]**	**1,534.51 [1,436, 1,674]**	*2,671.02 [2,497, 2,835]*	*2,601.42 [2,431, 2,760]*	*2,605.73 [2,507, 2,754]*
450	1,628.754 [1,448, 1,802]	1,498.42 [1,308, 1,678]	1,519.65 [1,419, 1,667]	*2,668.75 [2,487, 2,845]*	*2,589.35 [2,410, 2,763]*	*2,595.24 [2,495, 2,752]*
500	1,610.333 [1,421, 1,795]	1,463.01 [1,260, 1,653]	1,488.11 [1,386, 1,647]	*2,650.33 [2,453, 2,834]*	*2,560.97 [2,367, 2,737]*	*2,568.58 [2,469, 2,739]*

Numbers in brackets are 95% confidence intervals derived from nonparametric bootstrap. Alternatives in bold indicate the maximum value in each column. Alternatives in italic indicate nonfeasible solutions under the cross-compliance scheme (i.e., a restriction on nitrogen use)

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